Renewable Energy in Energy-Efficient, Low-Pollution Systems

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Abstract

Energy use accounts for the dominating fraction of total sulphur dioxide (SO_2), nitrogen oxide (NO_x), volatile organic compounds (VOCs) and carbon dioxide (CO_2) emissions. In this thesis, different strategies for reducing these emissions are evaluated, using a bottom-up approach. The thesis is divided in two parts. Part I (two articles) deals with how energy efficiency improvements and the increased use of renewable energy sources together can contribute to the reduction of emissions from energy use. Part II (four articles) focuses on energy from biomass as a potential option to reduce net CO_2 emissions from energy systems.

CO_2 emissions from electricity and heat production in western Scania, Sweden, can be reduced by 25% and the emissions of acidifying gases (SO_2 and NO_x) by 50% by the year 2010, compared with 1988 levels, using energy systems based on efficient end-use technologies, cogeneration of heat and electricity, renewable energy sources and low-pollution energy conversion technologies (Article I).

Exhaust-pipe NO_x emissions from the Swedish transportation sector can be reduced by 50 percent by the year 2015, compared with 1991, by implementing the best available vehicle technologies (Article II). Exhaust-pipe emissions of CO_2 can be stabilized at the 1991 level. With further technical development and the use of fuels from renewable sources of energy, NO_x emissions can be reduced by 75 percent and CO_2 emissions by 80 percent compared with 1991 levels.

Swedish biomass resources are large, and, assuming production conditions around 2015, about 200 TWh/yr could be utilised for energy (Articles III-VI). Major reductions in CO_2 emissions could be achieved by substituting biomass for fossil fuels in heat, electricity and transportation fuel production (Articles IV and VI). The cost of CO_2 reduction would be about US$50-150/tonne C when replacing fossil fuels used for heat production, US$50-175/tonne C when substituting fossil fuels used for electricity production, and US$180-340/tonne C when substituting fossil transportation fuels with biomass (Articles IV and V). Transportation fuels produced from cellulosic biomass are likely to be less expensive than transportation fuels from conventional biomass feedstocks such as oil plants, sugar-beet and cereals.

List of Articles

This thesis is based on the following articles:

PART I. ENERGY SYSTEMS STUDIES

Article I

Gustavsson, L., Johansson, B. and Bülow-Hübe, H. 1992. An environmentally benign energy future for Western Scania, Sweden, *Energy - the International Journal,* **17**, 809-822.

Article II

Johansson, B. 1995. Strategies for reducing emissions of air pollutants from the Swedish transportation sector, *Transpn. Res. -A*, **29A**, 371-385.

PART II. BIOMASS ENERGY

Article III

Gustavsson, L. and Johansson, B. 1994. Cogeneration: one way to use biomass efficiently, *Heat Recovery Systems & CHP*, **14**, 117-127.

Article IV

Gustavsson, L., Börjesson, P., Johansson, B. and Svenningsson, P. 1995. Reducing CO_2 emissions by substituting biomass for fossil fuels, *Energy - the International Journal*, **20**, 1097-1113.

Article V

Johansson, B. 1996. Transportation fuels from Swedish biomass - environmental and cost aspects, *Transpn. Res. - D,* **1**,47-62.

Article VI

Johansson, B. 1996. Will Swedish biomass be sufficient for future transportation- fuel demands?, *Energy - the International Journal*, **21**, 1059-1069.

Table of contents

Summary

The availability of inexpensive energy has been a key factor in the development of the industrial society. However, energy use also accounts for a large fraction of the emissions of pollutants to the air resulting in local, regional and global environmental problems. In the articles, which comprise the thesis, it is shown that nitrogen oxide (NO_x), sulphur dioxide (SO_2), and carbon dioxide (CO_2) emissions can be reduced significantly over the next 20-25 years if available and near-commercial technologies are implemented. This essay summarizes the results of the articles, and puts them into a wider perspective.

The first chapter presents a short overview of the importance of energy use for social and economic development, and introduces some of the problems associated with this energy use. The connection between energy use and negative environmental impact, especially the issue of climate change, is discussed in more detail in Chapter 2.

The bottom-up approach used in this thesis is described in Chapter 3 and it is compared with other available methodologies for energy systems studies. Specific methodological problems encountered in this work are also discussed in this chapter.

Different strategies for the reduction of emissions of pollutants to the air from energy use are described in Chapter 4. Energy efficiency improvements, the use of cleaner fuels and cleaner energy technologies, as well as the use of renewable energy sources, are discussed. Energy efficiency improvements can stabilize or even reduce energy use, while simultaneously allowing an increase in the level of energy services. Cleaner fuels, low-emission energy conversion technologies and exhaust gas treatment have historically been important measures in reducing the emissions of many compounds, such us lead, SO_2, NO_x and volatile organic compounds.

Swedish biomass resources are large, and, assuming production conditions around 2015, about 200 TWh/yr could be utilised for energy (Articles III-VI). Major reductions in CO_2 emissions could be achieved by substituting biomass for fossil fuels in heat, electricity and transportation fuel production (Articles IV and VI). The cost of CO_2 reduction is uncertain and differs between applications. It is, however, estimated that the cost would be about US$50-150/tonne C when replacing fossil fuels used for heat production, US$50-175/tonne C when substituting fossil fuels used for electricity production, and US$180-340/tonne C when substituting fossil transportation fuels with biomass (Articles IV and V). Transportation fuels produced from cellulosic biomass are likely to be less expensive than transportation fuels from conventional biomass feedstocks such as oil plants, sugar-beet and cereals.

The results of the scenarios presented in articles I, II, IV and VI are summarized in Chapter 5. It is shown that NO_x and SO_2 emissions from heat and electricity production

in Western Scania can be reduced by more than 50% and the emission of CO_2 by 25% from the 1988 level by 2010, using energy systems based on the most energy-efficient technology commercially available, cogeneration, renewable energy sources and low-pollution energy conversion technologies. Implementing the best available vehicle technology in a fossil-fuel based Swedish transportation system would reduce NO_x emissions by 50% compared with 1991 and maintain CO_2 emissions at the 1991 level by 2015. The introduction of more energy-efficient vehicle technologies and biomass could result in major CO_2 reductions in the transportation sector compared with 1991.

The potential emission reductions will probably not be fully achieved without implementing political measures. Various options such as economic incentives, regulations and R&D support are discussed in Chapter 6 .

1. Background

The availability of inexpensive energy has been a key factor in the development of the industrial society. The development of technologies for coal utilisation, including the steam engine, was one of the factors contributing to the industrial revolution of the 18th century (Dillard, 1967).[1] Coal remained the dominating commercial energy source until the 1960s when petroleum became more important.[2] Low petroleum prices were a major factor in the rapid increase in affluence in industrialised countries after the Second World War (Goldemberg et al., 1988). The electrification of society has played an especially important role in industrial development, allowing, for example, more flexible industrial localisation and organisation than older technologies (Schurr, 1984; Schön, 1990). It has also allowed the production of high-quality domestic services (e.g. lighting, refrigeration and cooking) now taken for granted in industrial societies.

The development of efficient transport systems has also contributed to economic development, by increasing the opportunity to achieve scale economics, utilising comparative advantages of different geographical areas and exploiting distant natural resources, see e. g. Dillard (1967) and Ville (1990). Mobility is regarded by many people in industrialised countries as an essential part of their welfare. The fraction of energy use devoted to transportation is growing in almost all countries (IPCC Working Group II).

The oil crises during the 1970s demonstrated society's vulnerability to increases in energy prices. These price increases struck the non-oil-producing, developing countries especially hard and an increasing share of their export incomes had to be devoted to paying oil bills and servicing external debts partly generated by oil imports. Developing countries are also burdened by the need for investments in energy supply infrastructure, demanding significant shares of their economic resources (Goldemberg et al., 1988). In the longer run, the dependence on depletable fossil fuels is unsustainable, although the proven reserves[3] of oil, natural gas and coal would last for approximately another 40, 60 and 230 years, respectively, at current rates of utilisation (British Petroleum, 1996).

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1 The steam engine had a two-fold connection to the utilisation of coal. Firstly, the steam engines were important for water-pumping necessary to exploit the coal resources. Secondly, the steam engines used for industrial production were one of the main end-use application for the coal produced.

2 For comparison, coal accounted for more than 80% of the global commercial energy use in 1925 and less than 30% in 1972 (Goldemberg et al., 1988). The proportion of oil increased from 13% to 46% of global energy use during the same period.

3 *Reserves* of mineral and fossil fuels are, according to the definition of the World Energy Council (1992) (BP uses a similar definition): "known resources of mineral and fossil fuels that, under the local conditions prevailing at the time of their assessment, may be economically exploited". In contrast *resources* of mineral and fossil fuels are "known and assumed, naturally occurring concentrations of mineral and fossil fuels that are either already of economic value or may be realised in the foreseeable future." Fossil fuel resources may thus become reserves either by being confirmed, by implementing technologies for utilisation that have lower costs, or by increases in fossil fuel prices. The

Energy use also causes serious threats to global security. Natural resources (energy being one of them) have been an important factor in many conflicts during the 20th century (SIPRI, 1986). The main oil reserves are located in a handful of countries, and about 70% of the known oil reserves are located in countries in the Middle East (British Petroleum, 1996). Promoting the stability of these countries has therefore been an important part of the strategic policies of the main world political powers (Goldemberg et al., 1988). Another threat to global security is the link between nuclear power and the risk of nuclear weapons proliferation (SIPRI, 1986; Goldemberg et al., 1988) Nuclear power, currently producing about 15% of global electricity, was expected during the 1970s and 1980s to be rapidly expanded.[4] Such an expansion would not only increase the risk of proliferation as more nations would gain access to materials suitable for nuclear weapon manufacture, but would probably also necessitate the introduction of plutonium breeder reactors and other systems requiring the processing, separation, and recycling of materials suitable for use in nuclear weapons (Goldemberg et al., 1988).

During recent decades, the environmental impact of energy use has been a major area of discussion and research. Although many policies have been implemented to reduce this impact, energy use is still a dominating contributor to many local, regional and global environmental problems, especially those connected with air pollution. Energy use in the transportation sector plays a particularly important role as emissions at street level pose a considerable health risk. Furthermore, the emissions of nitrogen oxides (NO_x), volatile organic compounds (VOC) and carbon monoxide (CO) from the transportation sector are high per unit energy used, compared with the emissions from heat and electricity production plants.

Several potential strategies for the reduction of emissions of air pollutants from energy use are presented in this thesis. Rather than proposing any specific strategy which may seem optimal based on certain criteria, the aim of this work was to identify different opportunities to reducing the environmental impact of energy use. The focus is on the Swedish energy and transport systems, with special emphasis on the areas of energy efficiency improvements, low-pollution technologies and the utilisation of renewable

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resource bases of conventional oil, gas and coal were estimated to equal 66, 130 and 1380 years of production, at current utilisation rates (IPCC Working Group II, 1996). The resource base of unconventional oil (oil shale, tar sands and heavy crude) and gas (gas in Devonian shales, tight sand formations, geo-pressured aquifers, and coal seams) are about 2 1/2 times larger than the resource base of conventional oil and gas.

4 In the projections from the World Energy Conference (1978) it was assumed that nuclear energy would increase from 5% of the primary energy supply in 1985 to 30% by the year 2020 (an average annual increase in nuclear primary energy of 8%). IIASA (1981) estimated that nuclear energy would provide approximately 20% of primary energy by 2030. The expected growth in nuclear power is much lower (1-3% per annum) in more recent studies, see e. g. IEA (1995) and the World Energy Council Commission (1993).

energy sources. The timeframe of the studies is 20-25 years, long enough to allow for major technological changes to take place in the energy and transport systems, but short enough to allow a reasonable understanding of the technologies that might play a role in the systems.

2. The energy–environment connection

Local, high concentrations of air pollutants near point sources have presented major problems for hundreds of years. The initial strategy used to address such problems was to build high chimneys to disperse the pollution over larger areas. Improved combustion and cleaning technologies have also contributed to reducing the local air pollution from point sources in many industrialised countries. Simultaneously, emissions from the use of motor vehicles have increased. The concentrations of sulphur dioxide (SO_2), CO, nitrogen dioxide (NO_2), VOC, tropospheric ozone (O_3) , suspended particulate matter (SPM) and lead (Pb) significantly exceed the WHO guidelines in cities both in industrialised and developing countries (UNEP and WHO, 1992). High concentrations of these pollutants have direct effects on human health, ranging from irritation in respiratory organs, increased susceptibility to respiratory diseases and reduced pulmonary function (SO_2, NO_2, O_3, SPM) to toxic effects (e.g. Pb, some VOCs). Furthermore, SPM and many VOCs, such as benzene and polyaromatic hydrocarbons, are highly carcinogenic.

By international comparison, the air quality in Sweden is relatively good, although NO_2 and O_3 levels locally exceed the national guidelines (Swedish Environmental Protection Agency, 1993a; Statistics Sweden, 1996a).[5] Furthermore, 100-1000 cases of cancer can be attributed annually to air pollution in Sweden (Official Report of the Swedish Government, 1996). About 50% of these cancer cases are lethal. Motor vehicle traffic is the dominating source of local air pollution. Other important sources are domestic biomass burning and industrial processes. For example, domestic biomass burning produces approximately 30% of the total anthropogenic VOCs in Sweden (Statistics Sweden, 1996a).

Acidifying gases are spread regionally and only 7% of the sulphur and 23% of the nitrate and ammonium nitrogen (also contributing to the eutrophication of soils and water) deposited in Sweden are emitted domestically (Statistics Sweden, 1996a). Swedish emissions are, on the other hand, transported and deposited in other countries.[6] Also, tropospheric ozone, produced from oxygen in the presence of NO_x, VOCs and sunlight, may cause damage hundreds of kilometres from the original source of emission.

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5 It should be observed that the Swedish guidelines for air pollution are low compared with the WHO guidelines. Whereas WHO guidelines for SO_2, CO, NO_x, O_3 and SPM are 350, 10000, 190-320, 100-200 and 70-230 $\mu g/m^3$, respectively, the corresponding values for Sweden are 200, 6000, 110, 120 and 90 $\mu g/m^3$, see Nilsson and Johansson (1995) for a specification of the data.

6 The deposition of sulphur in Sweden in 1994 was approximately 4.4 times greater than the Swedish emission, whereas the depositions of ammonium and nitrate nitrogen in Sweden were approximately 45% greater than the Swedish emissions (Statistics Sweden, 1996a)

The climatic conditions on earth are heavily dependent on the atmospheric concentrations of greenhouse gases, of which water and carbon dioxide (CO_2) are the most important. The concentrations of many greenhouse gases have increased considerably since the industrial revolution (Table 1). CO_2 contributes about 65% and methane (CH_4) 20% to the total direct radiative forcing (2.45 Wm^{-2}) of the anthropogenic greenhouse gases in the atmosphere (Table 1). Other compounds with major direct radiative forcing are nitrous oxide (N_2O), CFCs and HCFCs (Table 1). In addition, tropospheric ozone, produced indirectly from anthropogenic emissions, contributes approximately 0.4 ($\pm$0.2)Wm^{-2} to global average radiative forcing (IPCC Working Group I, 1996). The depletion of the stratospheric ozone layer and the emissions of tropospheric aerosols cause negative radiative forcing, reducing the greenhouse effect.

Table 1. Atmospheric pre-industrial and 1994 concentrations of CO_2, CH_4, N_2O, CFC-11 and HCFC-22; and recent rate of concentration change, atmospheric lifetimes and radiative forcing of these gases (IPCC Working Group I, 1996).

	CO_2	CH_4	N_2O	CFC-11	HCFC-22
Pre-industrial concentration	~280 ppmv	~700 ppbv	~275 ppbv	zero	zero
Concentration in 1994	358 ppmv	1720 ppbv	31~2 ppbv	268 pptv	110 pptv
Recent rate of concentration change	0.4%/yr	0.6%/yr	0.25%/yr	0%/yr	5%/yr
Atmospheric lifetimes (yrs)	50-200	12	120	50	12
Radiative forcing due to changes in greenhouse gas concentrations since pre-industrial time[a]	1.56 Wm^{-2}	0.47 Wm^{-2}	0.14Wm^{-2}	Note b	Note b

a Radiative forcing due to changes in greenhouse gas concentrations since pre-industrial time is 2.45 Wm^{-2} (range: 2.1 - 2.8 Wm^{-2}) in total for the direct effects of the main greenhouse gases (CO_2, CH_4, N_2O and the halocarbons).

b The direct radiative forcing due to CFCs and HCFCs combined is 0.25 Wm^{-2}. However, their net radiative forcing is reduced by 0.1 Wm^{-2} because they have caused stratospheric ozone depletion which gives rise to negative radiative forcing (IPCC Working Group I, 1996).

The concept of Global Warming Potential (GWP) has been developed to compare the impact of emissions of different greenhouse gases. The GWP is defined as the cumulative radiative forcing between the present and some chosen time horizon caused by a unit mass of the gas emitted now. The GWP differs depending on the time horizon studied, as a result of the different atmospheric lifetimes of the greenhouse gases. The uncertainty range for GWPs is typically ±35% (IPCC Working Group I, 1996). CO_2 emissions accounted for more than 60% of the global anthropogenic contribution to the greenhouse effect caused by 1990 emissions, while methane accounted for 15%, N_2O for 4%, and CFCs for 14%, recalculating the respective emissions to GWPs applying a 100 year horizon.[7] In Sweden, the corresponding values were 64%, 8%, 2% and 14% (Swedish Environmental Protection Agency, 1991).

Global anthropogenic CO_2 emissions are mainly the result of fossil fuel combustion and cement production (77%). Net emissions from changes in tropical land use contribute the remaining 23% (IPCC, 1994). About 25% of global anthropogenic CH_4 emissions are fossil-fuel related. Other important sources are enteric fermentation (20%), rice paddies (15%), landfills, animal waste and sewage (25%) and biomass combustion (11%) (IPCC, 1994). The most important sources of CO_2 and CH_4 emissions in Sweden are shown in Figure 1.

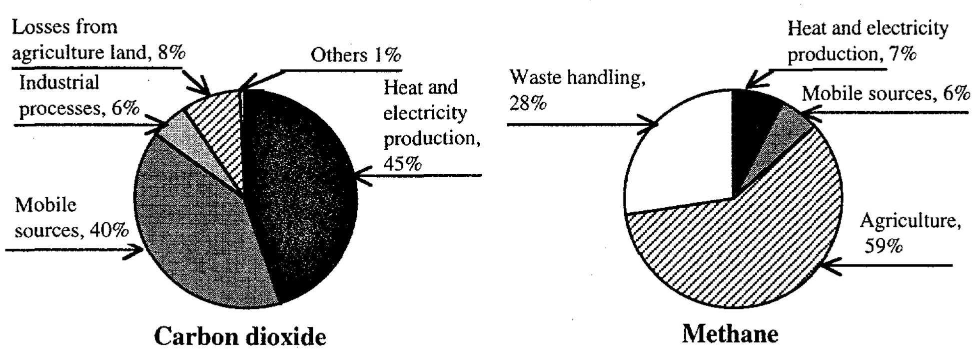

Fig. 1. Estimated proportions of emissions according to source for Swedish anthropogenic carbon dioxide (69 Mtonne/yr) and methane emissions (245 ktonne/yr), 1994. (Estimated by the author based on the Swedish Environmental Protection Agency (1995) and Rodhe et al. (1995)).

The environmental effect of increased concentrations of greenhouse gases in the atmosphere is difficult to assess. However, for the mid-range IPCC emissions scenario,[8] models project an increase in global mean surface temperature relative to 1990 of about 2°C by 2100 (IPCC Working Group I, 1996).[9] Increased temperatures are expected to affect precipitation levels, the distribution of vegetation zones, and average sea levels (the sea level is expected to rise as a result of thermal expansion of the oceans and melting of glaciers and ice-sheets). The effect of climate change will vary significantly between different areas of the world.

There is a risk that future climate changes may involve surprises. In particular, these arise from the non-linear nature of climate systems. When rapidly forced, non-linear

7 The impact of the greenhouse gases emitted over single year should not be confused with the greenhouse effect, shown in Table 1, resulting from the increased atmospheric concentrations of the total emissions of greenhouse gases since pre-industrial times.

8 Resulting in a doubling of the atmospheric CO_2 concentration relative to 1990 by 2100.

9 Combining the lowest IPCC emissions scenario with a low value of climate sensitivity results in a projected temperature increase of 1°C whereas a combination of the highest IPCC emission scenario and high climate sensitivity results in a projected temperature increase of 3.5°C relative to 1990 by 2100 (IPCC Working Group I, 1996).

systems are especially subject to unexpected behaviour. Examples of such non-linear behaviour include rapid circulation changes in the North Atlantic and feedback associated with terrestrial ecosystem changes (IPCC Working Group I, 1996).

The Swedish Environmental Protection Agency (1993c) has estimated that European emissions of sulphur must be reduced by 90% compared with 1980 and the emissions of NO_x and VOCs by 75 to 80% compared with the level at the end of the 1980s to solve the large-scale problems of acidification, eutrophication and high concentrations of tropospheric ozone. [10,11] IPCC estimated that CO_2 emissions would immediately have to be reduced by at least 60% to stabilize the concentration at the 1990 level (IPCC, 1990).[12] The IPCC Working Group I (1996) recognised that for the greenhouse gases "any eventual stabilized concentration is governed more by the accumulated anthropogenic emissions from now until the time of stabilisation, than by the way those emissions change over the period". Higher emissions in earlier decades thus require lower emissions later on to stabilize at a given concentration.

Air pollution is not the only environmental impact of energy use. Other negative impacts are the destruction of natural and cultural landscapes, noise, the production of radioactive waste and the depletion of non-renewable natural resources. The construction of hydro power plants has, in many cases, resulted in large areas being flooded, with negative effects on flora, fauna and the cultural landscape. The utilisation of other energy sources, fossil, nuclear and not least renewable energy sources, may also make use of large areas. The transport sector is the main source of noise. A significant fraction of the population (in Sweden 25%) suffers from noise levels higher than 55 dBA.[13] In addition to routine emissions and the risk of accidental emissions of radioactivity from nuclear plants, these plants produce radioactive waste which must be taken care of for thousands of years. Non-renewable natural resources are used to build power plants. Although

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10 That is to reduce the deposition of acidifying compounds below the critical loads, and to reduce the background concentration of tropospheric ozone during the plant growing season below $50 \mu g/m^3$. Furthermore, the ozone concentration level of $120 \mu g/m^3$ should not be exceeded for more than 12 hours/year, while the level of $150 \mu g/m^3$ should never be exceeded (Swedish Environmental Protection Agency, 1993c). The Swedish Environmental Protection Agency (1993b) defines critical loads as: "the highest load not leading to long-term adverse effects on the most sensitive ecosystems".

11 European and Swedish emissions of sulphur have decreased by approximately 40% and 80%, respectively, between 1980 and 1993 (NUTEK, 1996). European and Swedish NO_x emissions were reduced by 15% and 4%, respectively, between 1989 and 1993 (NUTEK, 1996).

12 The IPCC Working Group I (1996) estimated that CO_2 emissions would have to fall to the 1990 level by approximately 40 years from now and drop substantially (>80%) below the 1990 level subsequently to stabilize at a level of 450 ppmv (25% higher than current concentrations).

13 According to the Swedish Environmental Agency (1993a) research has shown that, on the basis of present knowledge, the level for good environmental quality may be set at 55 dBA at the facade of the building.

these material flows are currently small compared with other flows in society, they should be borne in mind when future technical solutions are evaluated. For example, the availability of some scarce materials may be a restriction for the widespread use of some types of solar cells (Andersson et al., 1996).

3. Methodologies for energy systems studies

The work described in this thesis is based on an engineering approach often called the bottom-up approach.[14] In Section 3.1 the general outlines of this approach are described and it is compared with other methodologies often used in energy systems analyses. In Section 3.2, more specific methodological problems concerning the articles constituting this thesis are discussed

3.1 Engineering and macro-economic energy systems models

3.1.1 Methodology description

There is a long tradition of modelling energy systems, and forecasting their future development, mainly for the purpose of energy planning. Methods used for forecasting energy use have varied significantly from relatively simple trend extrapolations, to more complicated macro-economic models. Many forecasts during the 1970s significantly overestimated future growth in energy demand (Goldemberg et al., 1988). This, together with the inherent difficulties involved in combining the results of these forecasts with social and environmental goals, increased the interest in focusing more on how energy was used. This has been the basis for several *bottom-up scenario studies* carried out from the end of the 1970s until today, see e.g. Goldemberg et al. (1988), Bodlund et al. (1989), and Johansson et al. (1993a).

Bottom-up methodologies are based on the recognition that consumers demand energy services, not energy per se. The same energy services can be produced with different levels of energy use depending on the technology used.

The working scheme of a typical bottom-up scenario study may be as follows, based on Christiansson et al. (1995):

(i) current and future levels of energy services are estimated,

(ii) quantitative physical data on different energy end-use technologies are collected, and scenarios for future energy use are designed, based on these technologies,

(iii) different supply scenarios are constructed and combined with the end-use scenarios,

(iv) costs and environmental impact are calculated for the different scenarios,

(v) obstacles in attaining these scenarios may be identified and the policy requirements needed to achieve a desired scenario may be analysed.

The most important assumptions made in bottom-up models are concerned with the energy service levels, costs, energy efficiencies and useful lifetimes of technologies

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[14] In the following, I will refer to the method used in this thesis as the bottom-up scenario approach when necessary to delimit it from engineering methodologies utilising optimization models.

currently in use and their alternatives, fuel and electricity costs, and the potential rates and limits of alternative technology penetration. Energy service levels are estimated outside the models and there is generally no feedback in the model from the energy sector to other sectors.

As alternatives to the bottom-up scenario approach used in the articles constituting this thesis, there are engineering methodologies which utilise *energy systems optimization models* to develop economically efficient energy systems. Such models are widely used, for national and regional energy systems, as well as for industrial systems and buildings , see e.g., Henning (1996), Lehtilä and Pirilä (1996), K. Nilsson (1993) and Gustavsson and Karlsson (1990). These models are designed to find the best combination of competing energy sources and conversion technologies using linear and non-linear programming methods. The optimization models are, in some aspects, related to the bottom-up scenario methodology described above. They are based on the collection of technology databases and the energy systems are designed from their techno-economical performance. The optimization models differ from the bottom-up scenario methods in that the optimization models are used to find energy systems that are *optimal* according to certain criteria, whereas the bottom-up scenario methods are not used for this purpose. Instead the scenarios are developed to identify *possible* future energy systems. Their characteristics are then compared without assuming that any of the identified systems would be optimal from any criteria. Although optimization methods may be useful for short- and medium-term energy planning, it can be questioned whether they are useful for developing long-term energy strategies, see e.g. Steen and Agrell (1991) for a discussion. To enable feedback between the energy sector and other sectors, work is ongoing to combine optimization models with macro-economic models, see Nyström (1995) and Wene (1996).

Energy use in *macro-economic models* (often called top-down models)[15] is primarily determined by macro-economic factors, such as energy prices, income levels, income and price elasticities of energy use, cross-elasticities between labour, capital and energy, and non-price-induced efficiency improvements.

Macro-economic methodologies include a variety of approaches. In energy-economy models the energy sector is linked to other sectors of society and changes in the energy sector result in changes in other sectors, and vice versa. The energy sector is usually treated in a rather aggregated way, although there are large differences between the models; see e.g. the discussion in Beaver (1993). Some models may focus on the energy

[15] There are a considerable number of macro-economic energy studies. Beaver (1993) reviews some of the models used. A review of some bottom-up and top-down studies can also be found in Wilson and Swisher (1993). Other examples of macro-economic energy studies are the World Energy Conference (1978), IIASA (1981), Manne and Scrattenholzer (1993) and Jorgensen and Wilcoxen (1993).

system, and estimate energy use from certain exogenous macro-economic data. Supply systems to cover this demand may be created using optimization or other more or less formal methods. Top-down models may be used both to predict future energy systems and to explore the effect of changing variables such as fuel prices and taxation. Macroeconomic models are primarily designed to describe market responses to changing prices, and by including other sectors it is possible to estimate the effect on the whole society of different energy policies. They describe economic history quantitatively and apply historical observations to the future (Wilson and Swisher, 1993). This implicitly means that future relationships are assumed to resemble past ones. Problems may, however, arise when using top-down models to analyse the effects of large changes in the energy market since the changes may exceed the ranges (of for example energy prices) over which the assumed values are valid. Such changes may well be realistic under the pressure of serious environmental problems.

An important factor when evaluating different methods for energy systems analysis is the transparency of the method. There are always uncertainties involved when modelling future energy systems. Since energy studies are often used as a basis for policy decisions, it is important that assumptions and methods be easy to understand, making the results easier to evaluate. The bottom-up scenario methodology, designed to identify opportunities in a changeable world, is simple and transparent and seems especially useful for developing and evaluating long-term energy strategies with genuine uncertainties.

3.1.2 Estimating CO_2 mitigation costs using bottom-up and top-down methodologies

During the latest decade, both bottom-up and top-down models have been widely used to estimate costs for CO_2 reduction. The results of these studies have differed significantly, a fact that has lead to several analyses of these differences, see e.g. Wilson and Swisher (1993) and the IPCC Working Group III (1996). One important conclusion of these assessments is that the results of bottom-up and top-down studies have differed not only as a result of different basic macro-economic and technology assumptions, but because of some inherent differences in the methodological approach.

The cost calculations in bottom-up studies (for example those in this thesis) usually include direct costs (fuel costs and investment and operating costs for end-use and supply technologies) for specific technical measures or whole energy systems. Such costs are relatively simple to calculate, although the amount of data necessary is large. Changes in the energy system may, however, also affect other economic sectors. In energy-economy models such effects on the total economy can be included and the cost difference between different energy policies may be estimated from differences in Gross Domestic Product (GDP). It must be added that GDP is also a very rough measure of welfare. Estimating welfare costs would be more suitable for evaluating CO_2 mitigation costs.[16]

Proponents of the bottom-up approach claim that there are market barriers hindering economic energy efficiency improvement options from being implemented. Such market barriers may be lack of information, unsuitable economic incentives and that different investment criteria are used for investments in energy end-use and supply technologies. Advocates of the top-down approach, on the other hand, implicitly assume that all profitable energy efficiency improvements have been utilized. Bottom-up studies are often criticised for underestimating the cost of energy efficiency improvements since they only calculate direct costs for different options. Apart from these direct costs, there are transaction costs, including, for example, the cost of obtaining information on different technologies and costs related to risks and uncertainty. There may also be slight differences (for the better or the worse) in the energy service provided due to the use of more energy-efficient technology, which is not always correctly assessed in the bottom-up studies. Transaction costs and other limits on implementation can, however, be estimated and included also in bottom-up studies (Christiansson et al., 1995). Bottom-up advocates often focus on how to remove the barriers for energy efficiency technologies. Whereas the macro-economic approach usually regards energy prices as the dominating factor which can influence energy use, bottom-up proponents also focus on other options such as increased information, standards and regulations.

The discount rate is one macro-economic assumption which heavily influences both estimates of CO_2 mitigation costs and estimates of damage costs due to CO_2 emissions. High discount rates will make investments in CO_2-reducing equipment expensive, and the present cost of future damage due to CO_2 will appear low. This makes investments in technologies for CO_2 reduction seem rather unprofitable in a cost-benefit analysis. The discount rate in bottom-up studies can be chosen arbitrarily, and is often taken to be equal to interest rates used by public companies for long-term investments. In top-down models, discount rates for energy efficiency improvements are based on pay-back times applied in companies and households. These rates are usually much higher than the discount rates used for energy supply systems. This makes the energy efficiency improvements smaller than would be the case if a common discount rate were used for investments in energy supply and energy end-use.

[16] Some reasons why the GDP is not a good measure of welfare are discussed by the IPCC Working Group III (1996): (i) the distribution of GDP between investment and consumption affects welfare, (ii) human welfare does not increase linearly with consumption, (iii) GDP does not account for the relationship between distribution of income and welfare, (iv) environmental degradation reduces welfare but does not result in a corresponding reduction in the GDP.

Work is in progress to bridge the historical gap between the top-down and bottom-up methodologies; see the IPCC Working Group III (1996) and Krause (1996) for a discussion. More recent bottom-up models increasingly include behavioural aspects and expand the details of non-energy factors in their models, whereas more detail on energy end-uses and energy supply technologies is included in more recent top-down models (IPCC Working Group III, 1996). The IPCC Working Group II (1996) has created CO_2 emission scenarios using both bottom-up and top-down methodologies, and it has been possible to arrive at similar results for both methods. The IPCC Working Group II (1996) concludes that "the large differences in results often observed between top-down and bottom-up modelling exercises are not due to irreconcilable differences between the very different approaches, as some have suggested, but rather to differences in assumptions".[17]

3.2 Methodological problems in the studies described in this thesis

In the preceding section, the main methodological approaches employed in energy systems studies were presented, among them the bottom-up scenario approach used in this work. In this section specific methodological problems encountered in the studies described in this thesis will be discussed.

The scenarios developed in this thesis are not intended to reflect the most probable energy systems in the future, but to illustrate the inherent advantages and disadvantages of different technologies. This illustration is accomplished by creating technically consistent scenarios which focus on some interesting aspects of the energy systems. For example, systems dominated by renewable energy sources are compared with fossil-fuel-based systems, and systems with large fractions of cogeneration are compared with systems based on separate heat and electricity production. However, when creating the scenarios, important features of the energy system and inherent economic restrictions which might prevent the implementation of a certain technology in some applications are taken into consideration. Such restrictions are discussed and evaluated parallel with the scenario creation process. Implementation issues have not been analysed in the articles although their importance is acknowledged. Neither has any feedback from changed energy systems on the energy service levels been analysed.

[17] However, the energy balances in these top-down scenarios are based on an exogenous energy end-use improvement rate that increases from 0.5%/yr by 2005 to 2%/yr by 2050. This means, that to achieve the results of the bottom-up approach the top-down modeller no longer base their assumptions on historical records. This is a major change in the traditional way of using macro-economic statistics in energy modelling, making the approach more similar to the bottom-up approach.

Current fossil fuel prices have been used for the cost calculations in all the studies. The future prices of fuels are uncertain and will probably change. For example, the United States Department of Energy (1992) expects world oil price to more than double between 1989 and 2030. Johansson et al. (1993b) assume, however, that the world oil price in 2030 will be not much different from today, if a renewable intensive global energy scenario is realised. This would be the result of competition between renewable and conventional energy sources, causing a downward pressure on energy prices. Using current fossil prices seems to be as reasonable as using some of the existing diverging forecasts of future fossil fuel prices. It is important to realise, however, that increased fossil fuel prices will improve the economic competitiveness of both energy efficiency improvements and renewable energy sources, compared with the results presented in the articles

For biomass, fuel costs are taken as production cost excluding subsidies. Currently, the agricultural subsidies in Europe are substantial, which could make the price of biomass-based fuels lower than the production cost. With large-scale introduction of biomass, the biomass prices may rise as the resource becomes scarce. Estimating such price changes requires modelling, not only including the energy systems but other biomass-using sectors such as the forest and agricultural sectors. This is, however, beyond the scope of this work. Instead of including the scarcity aspect in the economic calculations, scarcity is reflected in different measures of resource efficiency (Articles III-V).[18]

In the articles, estimates of future biomass potentials are based on assumed future crop productivity and land available for biomass utilisation. Organisational, time-related constraints regarding the plantation of energy crops on arable land and the utilisation of large amounts of logging residues have not been analysed. Such constraints might affect the amount of biomass which can be practically utilized at a given time.

Comparing technologies that are new or still under development is difficult. Cost estimates for new technologies are especially uncertain as many of these technologies have not yet been demonstrated in large-scale applications. It is, however, necessary to include such technologies in a comparison to avoid focusing only on available but costly and relatively inefficient technologies. Large-scale implementation has been assumed when estimating costs for new technologies. The cost for electricity and transportation

[18] In Article III the resource efficiency measures studied were (i) amount of biomass required to produce one unit of heat and one unit of electricity and (ii) reduced amount of CO_2 per unit biomass (kg C/MWh). In Article IV, this latter measure was used together with (iii) reduction in CO_2 per unit area of land used for biomass production (tonne C/ha, yr). In Article V reduction in CO_2 per unit area of land used for biomass production was the only measure expressing resource efficiency.

fuels produced in pilot plants may be significantly higher than the cost expected for electricity and transportation fuels produced in future commercial plants. The costs of end-use technologies (e.g. vehicles) could also be expected to be higher when produced in small numbers than in mass production. The impact of new technologies on the environmental situation will only be minor before they become more widely used. Therefore, it is useful to visualise the economic and environmental impact of large-scale introduction to evaluate the suitability of different technologies in the future. It is, however, important to analyse current costs, when developing incentives for new technologies since they may have to be stronger in the implementation phase than later, when the costs have been brought down through learning, technological improvements and mass production.

Emissions of energy use arise from energy extraction, transportation, conversion, and end-use. For a complete analysis it is important to consider all these potential sources of emissions. In many cases the emissions from fuel combustion are much greater than the emissions from other parts of the life-cycle. In other cases, emissions from energy extraction, conversion and transportation may be significant compared with the emissions from fuel combustion (Ecotraffic, 1992). For renewable energy sources, net CO_2 emission arises from the use of fossil fuels in producing biomass, solar panels, wind power plants, etc.

The results of life-cycle analyses are heavily dependent on the assumptions on which they are based. For example, the life-cycle NO_x emissions from a vehicle using biomass-based methanol will depend heavily on which fuel and technology were used for biomass production and transportation (Article II). Using electric vehicles results in zero emissions from end-use, but may result in as high or higher life-cycle emissions of CO_2, SO_x and NO_x than for conventional passenger cars if the electricity is produced inefficiently and with polluting fuels (OECD, 1993). Emissions may, however, be significantly lower, using modern natural-gas or biomass-based electricity production plants, than for petrol-fuelled passenger cars (Article II).

It is of great importance to study life-cycle emissions for the competing technologies when considering major changes in the energy system. In the studies described in Articles II, IV and V a life-cycle perspective was applied when comparing different fuels for the production of heat, electricity and transportation fuels. The data presented in these articles, concerning life-cycle emissions, were taken mainly from already existing life-cycle analyses. Calculations were, however, made whenever necessary to illustrate aspects not covered in other studies. Furthermore, Articles IV and V report on original, elaborate assessments of fuel-cycle energy use for different biomass-based fuels to evaluate their potential in reducing CO_2 emissions when used for the substitution of fossil fuels.

It was assumed in this work that utilising sustainably grown biomass for energy does not produce any net emission of CO_2, as long as biomass is used for the necessary inputs for fuel production. This is a simplified assumption which does not take all aspects of the complicated carbon cycle into consideration. The effect of biomass utilisation on carbon balances is heavily dependent on the timeframe and the type of biomass studied, see Schlamadinger et al. (1995) and Schlamadinger and Marland (1996). In the very short term (<20yrs) the assumption might be very inaccurate for logging residues, but it improves when dealing with the greenhouse effect of biomass and fossil fuels combustion over a longer time period. The method used probably slightly overestimates the potential CO_2 reduction and underestimates the cost of CO_2 reduction when substituting logging residues for fossil fuels. For short-rotation forestry crops (here represented by *Salix*) the assumption seems to be quite accurate also in the shorter perspective. The potential for CO_2 reduction will, however, probably be slightly underestimated and the cost of CO_2 reduction slightly overestimated, since the expected carbon build-up in soils when switching from annual crops to short-rotation forest has not been included in the calculations.

4. Strategies for reducing emissions from energy use

The suitability of technical strategies for emission reductions depends on the type of pollutants, and the activity from which the pollution is emitted. Emission-reduction measures may include the introduction of new or improved conventional fuels, improved combustion technologies, technologies for exhaust gas treatment, and energy efficiency improvements (EEIs). EEIs are especially important from the perspective of sustainable development since they simultaneously reduce not only energy demand, and in principle all types of air pollutants[19], but also other environmental impacts of energy use resulting from extraction, conversion and end-use of energy. EEIs, together with the use of non-fossil energy sources are also especially important in reducing CO_2 emissions. In the short term, EEIs provide cheaper CO_2 reduction than the use of alternative energy supply options in most countries (IPCC Working Group III, 1996).

It is feasible to remove CO_2 from the exhaust gases of fossil-fuel power stations but this reduces the conversion efficiency and significantly increases the cost (IPCC Working Group II, 1996). Another approach is to produce hydrogen-rich fuels from fossil fuels, a method also generating a by-product stream of CO_2 which could be stored in, for example, exhausted natural gas fields and oceans. The potential for depositing CO_2 may be significant, especially in oceans [20], but the environmental impact of large-scale ocean deposition of CO_2 has not yet been sufficiently analysed (IPCC Working Group II, 1996).

4.1 Energy efficiency improvements

EEIs have been highlighted as a central strategy for creating a sustainable energy system; see e.g. the World Commission on Environment and Development (1987) and the United Nations Conference on Environment and Development (1992). EEIs or energy conservation are defined, in contrast to energy savings, as measures that reduce energy use while maintaining energy service levels. Energy savings, on the other hand, reduce energy use by reducing energy service levels. This work has focused on EEIs, and only solutions not expected to affect energy service levels have been included in the calculations. In reality, however, many EEIs result in a slight change in the quality of energy services,

[19] Efficiency improvements in supply systems may result in increased NO_x emissions since these emissions are mainly the result of the reaction between oxygen and nitrogen in air at high temperatures.

[20] The estimated storage capacity in exhausted oil and gas wells ranges between 130 and 500 GtC and in saline aquifers between 90 and 2500 GtC. More than 1200 GtC could be deposited in the ocean (IPCC Working Group II, 1996). After several hundreds of years some of the carbon deposited in the oceans may escape to the atmosphere. For comparison, the annual global anthropogenic emission of CO_2 is approximately 7 GtC/yr. The oceans contain about 38000 GtC.

although often for the better. For example, indoor climate may be easier to control in a well-insulated house.

Although not considered in this study, energy savings resulting from changes in behaviour and in the quality of the energy services provided may be significant.[21] For example, by reducing the indoor temperature by only 1°C, energy requirements for space heating would be reduced by 5% for a typical Swedish one- or two-dwelling building (Elmroth et al., 1987). Vehicle sizes and performance have substantial impact on the energy required for a certain transport service. Environmental taxes and many other policy options aimed mainly at improving the technical performance of the energy system will induce not only EEIs but also energy savings. Furthermore, behavioural changes are often the main short-term response to increased energy prices (Hallin, 1988).

Energy efficiency improvements can be divided in efficiency improvements in energy use and in energy supply. There are, however, links between these two areas. The use of electricity in Sweden has increased significantly since the beginning of the 1970s at the expense of the use of fuels. The expansion of electricity has often led to increased end-use energy efficiency, but not always to increased system efficiency.[22] The increased use of electricity for space and hot -water heating in residential and service buildings has been large and currently accounts for about a quarter of the total Swedish annual electricity use. Space and water heating is a strategic area for reducing electricity demand as nuclear power in Sweden will be phased out, according to a parliamentary decision.[23]

In Article I, the energy system (excluding the transportation sector) in western Scania in southern Sweden is analysed. It was concluded that by 2010 the energy use could be more than 20% lower if technologies with energy efficiencies corresponding to those of the best available technology on the market in 1988 were used, instead of technologies with energy efficiencies corresponding to those of the average used technology in 1988 (Table 2). The potential for EEIs for electrical appliances in the residential and service sectors is especially large. In Article II, the Swedish transportation sector was the subject of investigation. Using vehicles with the highest energy efficiencies available in 1991

21 It is possible to identify changes in the quality of energy services as long as the services are defined on a rather aggregate level; for example as heated floor areas or passenger-km. Changes in room temperatures or vehicle comfort can in such cases be regarded as changes in the quality of the energy service. The definition of appropriate energy services includes inherent difficulties. For example, in the present work, the transport service is expressed as passenger-km, a commonly used indicator of transport energy services. It could, however, be argued that travelling by cars includes many other aspects than just going from one place to another, see e.g. Tengström (1992). On the other hand, it might also sometimes be possible to achieve the same service achieved by the journey by using another mode of communication.

22 Here, system efficiency includes both end-use efficiency and efficiency of energy supply.

23 The reduction in electricity use for heat production was one of the main short-term measures proposed in the Swedish three-party energy agreement in February 1997 to manage the closure of two Swedish nuclear plants in the forthcoming five years (Svenska Dagbladet, 1997).

would result in more than 10% lower energy use by 2015 compared with vehicles with efficiencies equal to the 1991 average in new vehicles (Table 3). Energy use could be reduced even more if technologies available as prototypes in the base-years of the studies could be utilized.

Table 2. Energy use in 1988 and in scenarios for 2010 for different sectors in western Scania (Based on Article I). The transportation sector was not included in the study.

Sector	Final energy use in 1988 TWh	Final energy use in 2010[a] Frozen Efficiency[b] TWh	Efficiency[c] TWh	High Efficiency[d] TWh
Residential sector	7.9	9.1	7.3	6.7
Service sector	3.1	4.5	2.9	2.8
Industry	5.9	7.6	6.1	5.9
Agriculture	1.2	1.2	0.9	0.6
Total	**18.1**	**22.5**	**17.3**	**15.9**

a The scenario assumes an increase in heated floor area of 4% in one- and two-dwelling buildings, 35% in multi-dwelling buildings, 17% in buildings for education and research, 29% in buildings for health care and 40% in buildings for other services, between 1988 and 2010. The growth in production in the industrial sector was assumed to be 64% between 1988 and 2010. For more information on the assumptions of the energy service levels, see Article I.

b The average energy efficiency is assumed to remain at the same level as in 1988.

c The average efficiency in 2010 for appliances with a life-time shorter than 15-20 yrs is equivalent to the efficiency of the most efficient technology available in 1988. In existing buildings, efficiency improvements in space and water heating are made in connection with normal maintenance except for minor measures which are cost effective on a stand-alone basis.

d The efficiency in 2010 is equivalent to the efficiency of technologies that today exist as prototypes but are not yet commercially available.

Table 3. Energy use in the Swedish transportation sector in 1991 and in scenarios for 2015 (Based on Article II and B. Johansson (1993)).

Sector	Final energy use in 1991 TWh	Final energy use in 2015[a] Scenario AST[b] TWh	Scenario BAT[c] TWh	Scenario IT[d] TWh
Passenger cars	49	55	45	35
Buses	3.2	3.0	2.6	2.1
Lorries	15	17	15	12
Trains	2.8	3.6	3.6	3.2
Sea transport	5.3	8.8	8.0	6.7
Air transport	3.0	6.0	6.0	5.2
Total	**78**	**93**	**80**	**64**

a Swedish passenger and goods transport were assumed to increase by 30% and 50%, respectively, between 1991 and 2015.

b AST = Average Sold Technology. Average energy efficiencies in 2015 are assumed to be equal to the average of vehicles sold in Sweden in 1991

c BAT = Best Available Technology. Average vehicles used in 2015 are assumed to have the highest energy efficiencies existing for vehicles that were commercially available in Sweden in 1991.

d IT = Improved Technology. The assumed average energy efficiencies for 2015 are equal to efficiencies of vehicles currently available as prototypes but not yet commercially available

The technologies included in the scenarios in Articles I and II were those commercial or near commercialisation. For example, neither battery- or fuel-cell-powered electric vehicles, nor ultra-light vehicles were included in the scenarios. Fuel-cell-powered vehicles are expected to be 2-3 times as energy efficient as current state-of-the art vehicles with internal combustion engines (Johansson et al., 1993a). There are also studies (Lovins et al., 1993) indicating that the energy use of a passenger car could be as low as 0.1 l/10 km (i.e. less than one fifth of the level used in scenario IT in Article II). This could be achieved by combining energy-efficient drive trains with ultra-light composite materials, without sacrificing safety or comfort. Furthermore, residential buildings can be constructed which use less than 50 kWh/m^2, yr for space and water heating, i.e. less than 65% of the value used in the scenarios in Article I (Elmroth, 1989). Thus, the energy systems in the scenarios in articles I and II are by no means near the most efficient conceivable.

The energy efficiency potentials discussed in the articles are techno-economic potentials. Although they seem to be beneficial from society's point of view (even without an evaluation of the external costs of energy) there are several barriers to the implementation of the technologies, see Chapter 6.

Energy efficiency in energy supply systems is the focus of Articles III and IV, but is also extensively discussed in Articles I and VI. The reduction of losses in the distribution system is one aspect of energy efficiency. Losses in Swedish distribution systems are, however, relatively small. Therefore, only minor reductions in total energy use can be achieved by efficiency improvements in distribution. The importance of cogeneration of heat and electricity for an efficient, low-pollution energy system is demonstrated in several of the articles included in this thesis. Widespread use of cogeneration in western Scania could reduce CO_2 emissions from a fossil-fuel based energy system by 10% compared with the case in which heat and electricity are produced separately in boilers and condensing plants (Article I). The large district heating systems are of strategic importance for the Swedish potential for cogeneration. District heating provides approximately 10% of the final energy in Sweden, and is the dominating source of heating in residential and service buildings (NUTEK, 1996; Statistics Sweden, 1996b). In Article III, it is shown that Swedish district heating systems offer a potential for biomass-based cogeneration of approximately 20 TWh/yr (approximately 15% of current Swedish electricity production), provided that new technologies under development, with electricity-to-heat ratios of about 1, are used.

There is also a major potential for cogeneration in industry. In western Scania the potential for the production of cogenerated electricity in industry was estimated to be equal to 10-20% of the electricity demand in the scenarios for 2010 (Article I). Cogeneration of heat and electricity could thus technically satisfy a significant fraction of the electricity demand. A strategy for increasing the energy efficiency of the Swedish energy system would include the expansion of district heating systems at the expense of electric boilers and electric resistance heating. The main drawback in the expansion of district heating is the large investment costs, making it a viable option only where heat densities are large. In very energy efficient houses, electric heating may also have advantages due to low investment costs in the heating system. Wherever cogeneration is not a viable solution, electric heat pumps may have a major role to play in future energy systems as they produce heat efficiently from electricity.

4.2 Cleaner fuels and energy conversion technologies

Improved fuel quality, fuel switching, low-emission combustion technologies, and technologies for exhaust gas treatment offer important complements to energy efficiency improvements for achieving emission reductions. Such options may reduce emissions of certain compounds much more efficiently and much more rapidly than energy efficiency improvements alone.

Fuel quality is important in determining the emission level of several pollutants, such as sulphur, lead and specific harmful hydrocarbons. Reductions of the sulphur content of fuel oils and diesel, together with a switch from oil to natural gas and electricity from nuclear power plants, and the implementation of equipment for exhaust gas treatment, have contributed to the 80% reduction in sulphur emissions achieved in Sweden since 1980. The lead content of petrol has been reduced in Sweden since the beginning of the 1970s. This reduction was followed by the introduction of unleaded petrol in the middle of the 1980s, as a prerequisite for the introduction of three-way catalytic converters. Leaded petrol is no longer sold in Sweden. In the USA, much effort has been devoted to developing reformulated gasoline with lower contents of harmful compounds, and fuel properties which reduce the evaporative emissions.

Using coal to produce a certain amount of heat and electricity will result in much higher emissions of greenhouse gases than using natural gas (Wilson, 1990, IPCC Working Group II, 1996). This is the result both of the much higher carbon content in coal (103 g C /MJ) than in natural gas (56 g/MJ), and less efficient technologies for energy conversion. The use of oil for heat and electricity production will result in greenhouse gas emissions that are lower than for coal but higher than for natural gas. Most fossil transportation fuels (with the exception of fuels from coal) will produce similar amounts of greenhouse gas emissions (IEA, 1993). A switch to renewable energy sources and energy efficiency improvements are necessary to achieve substantial reductions in greenhouse gas emissions in the transportation sector.

Emissions other than carbon dioxide will also be affected by fuel changes. For example, using natural gas instead of oil and coal will result in significant reductions in sulphur emission. Especially important are the fuel choices in vehicles, where the combustion is more difficult to control than in stationary applications.

Technologies for exhaust gas treatment have the potential of reducing emissions of SO_x and NO_x by 80-90% at electricity- and heat-production plants. Such technologies, together with the use of low-sulphur fuel, are the main options used for the reduction of NO_x and SO_2 emissions in the scenarios in Article I .

Three-way catalytic converters in petrol-fuelled vehicles reduce CO, VOC and NO_x emissions by 80-90% when they are functioning. More than 90% of the CO and VOC emissions from passenger cars equipped with catalytic converters are, however, emitted during the first kilometre after cold start before the catalytic converter starts functioning (Lundin and Björklund, 1991). Shortening the warm-up time of the converters, improving fuel-air preparation and implementing exhaust gas recirculation, would enable a further reduction of CO, VOC and NO_x emissions from passenger cars by 80-90% compared with current levels (Egebäck, 1996).[24] Three-way catalytic converters do not work with diesel engines and the reduction of NO_x emissions is therefore much more difficult in this case.[25] NO_x emissions from heavy-duty vehicles are therefore likely to account for a larger share of the total transport emissions in 2015 than at the beginning of the 1990s (Article II).

4.3 Renewable energy sources

There are several reasons why interest should be taken in renewable energy sources. Local and regional environmental impact may sometimes be reduced by replacing fossil fuels with renewable energy sources. If well managed, renewable energy sources contribute much less to the greenhouse effect than do fossil fuels. Fossil fuels, in particular oil, are more unevenly distributed over the world than renewable sources of energy, resulting in a less secure supply. Especially for non-oil producing, developing countries the importation of fossil fuels imposes a heavy burden on foreign exchange. Increased use of domestic renewable energy sources may relieve this burden. Finally, in the longer run, the dependence on depletable fossil fuels is unsustainable.

In the current work, however, most of the interest in renewable energy sources is focused on their potential to reduce CO_2 emissions. The reason for this is the judgement that the issue of climate change will be the most important reason for increasing the use of renewable energy sources in the industrialised world during the time period studied (20-25 years). New combustion technologies and technologies for exhaust gas treatment can be expected to reduce the relative advantages gained by using energy carriers from

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24 Egebäck (1996) estimates that the emissions of CO, VOC and NOx from a passenger car of 2010 model could be less than 5% of the emissions from a car of 1988 model, calculated over the total life-times of the vehicles.

25 VOC and CO emissions from diesel engines are much lower than from Otto engines. Furthermore, oxidising catalytic converters could be used to reduce these pollutants from diesel vehicles.

renewable energy sources in terms of VOC, particulate and NO_x emissions; see e.g. Egebäck (1996). Many of the energy carriers with low emissions of VOC, NO_x and particulates, e. g. methane gas and methanol, can also be produced at lower costs from fossil fuels than from renewable energy sources during the time-frame studied. Increased CO_2 concentrations in the atmosphere also seem to be a more acute problem than the depletion of fossil fuel resources. However, prices of fossil fuels might increase, as a result of higher exploitation costs, if fossil fuel demand continues to increase.

The global potential of renewable energy sources is uncertain, but large, Table 4 (see for example Jackson (1992), Johansson et al. (1993) and IPCC Working Group II (1996) for a discussion). The focus in this thesis is, however, on the utilisation of Swedish renewable energy sources. Biomass is extensively discussed in the articles and will also be discussed in the following section. Hydro, wind and solar energy, also of potential interest in Sweden, will also be discussed below.

Table 4. Current global use of renewable energy, global renewable energy potential by 2020-2025, long-term technical potential for renewable energy and annual natural energy flows (IPCC Working Group II, 1996). The current global energy use is approximately 385 EJ/yr.

	Current global use EJ/yr	Global Potential by 2020-2025[a] EJ/yr	Long-Term Technical Potentials[b] EJ/yr	Annual Flows EJ/yr
Hydro	21	35-55	>130	>400
Geothermal	<1	4	>20	>800
Wind	-	7-10	>130	>200000
Ocean	-	2	>20	>300
Solar	-	16-22	>2600	>3000000
Biomass	55	72-137	>1300	Not available
Total	**76**	**130-230**	**>4200**	**>3000000**

a Estimates of practical potentials which could be achieved by 2020-2025. According to the IPCC Working Group II the concept can be used in a similar fashion to energy reserves for fossil fuels, with the fundamental difference that renewable potentials represent annual flows available, in principle, on sustainable basis indefinitely, whereas fossil energy reserves and resources, although expanding in time, are fundamentally finite quantities.

b The long-term technical potential can be used in a similar fashion to fossil energy resources, conventional and unconventional, but are fundamentally different due to their renewable characteristics as discussed in note a.

4.3.1 Biomass

The current global use of biomass[26] is difficult to estimate since most of biomass use is non-commercial. A recent estimate is that biomass accounts for 15% of the world energy use (Hall et al., 1993).The percentage contribution to total energy use in Sweden is

[26] In this thesis the term biomass includes energy crops and forest, crop and dung residues, while peat and municipal solid waste are excluded. Residues from the forest industries such as black-liquor are included in the biomass potential. The potential from dung residues and sewage in Sweden is estimated as the energy content of potential biogas production from these sources.

approximately the same (NUTEK, 1996). The use of biomass has increased significantly in Sweden since the beginning of the 1980s (Figure 2). Since 1990 the increase has been especially rapid in district heating systems, mainly as a result of the introduction of carbon taxes on fossil fuels for heat production.

The main environmental advantage of using biomass for energy production is, as discussed in Section 3.2, that it will, if sustainably managed, in principle not contribute to increased CO_2 concentration in the atmosphere. The use of biomass for carbon storage has sometimes been proposed as an alternative to using biomass for energy. However, studies have shown that, in the long-term, it is more effective for CO_2 reduction to grow biomass for CO_2 abatement through substituting fossil fuels, than growing standing biomass for carbon storage (see e.g. Schlamadinger and Marland, 1996). The most important reason for this is that the carbon fixation in biomass slows down significantly as the tree becomes older and the forest eventually reaches an equilibrium where the build-up and decomposition of biomass is balanced.

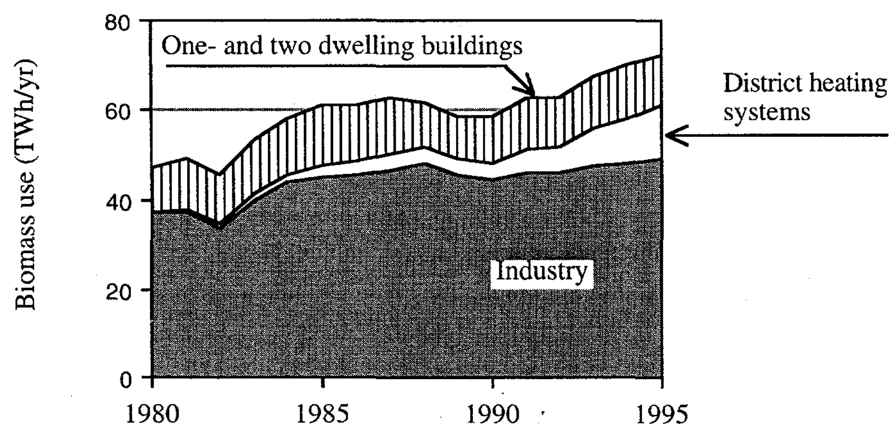

Figure 2. The use of biomass, 1980 - 1995, in Sweden (NUTEK, 1996).

Large-scale biomass utilisation seems to be compatible with preserving long-term productivity of soils and the preservation of biodiversity (Articles IV- VI). For this purpose it is important to recirculate nutrients, to leave some residues on the ground and to exempt the areas most important for biodiversity from intensive forestry and agricultural utilisation. Perennial crops (such as ley crops or Salix) have the potential to improve the long-term productivity of soils, and reduce nitrogen leakage and pesticide utilisation compared with the cultivation of conventional annual crops (Articles IV- VI). Biomass plantations cultivated for energy purposes can also play a role in strategies for reforestation of deforested and degraded land (Hall et al., 1993).

In Articles III-VI, it has been estimated that the annual biomass energy use could increase from the current 70 TWh to approximately 200 TWh by increasing the use of forest and agricultural residues, and by growing energy crops on surplus arable land not needed for food production. For comparison, the use of fossil fuels in Sweden was about 240 TWh in 1995.

In order to utilise biomass energy, some energy input (directly as fuels or indirectly through machinery, fertilisers, seed, etc.) is necessary for biomass production, and for transportation to conversion facilities and to end-use customers. It has been shown that the energy input may be quite significant for annual crops but rather low for perennial crops (e.g. Lucerne and Salix) and logging residues even under current production conditions (Table 5). The development of new cultivation practices is expected to increase the potential output and reduce the energy use in biomass production (Table 5).

Table 5. Net energy yield and energy output/input ratios for biomass production in Sweden under current production conditions and estimated production conditions in 2015 (Börjesson, 1996). All energy values in this table are expressed as higher heating values.[a]

	Current production conditions		Production conditions around 2015	
	Net energy yield[b] GJ/ha, yr[b]	Energy output[c] /input ratio	Net energy yield[b] GJ/ha, yr	Energy output[c] /input ratio
Energy crops				
Wheat[c]	111	6.7	160 (154)	11 (8.2)
Rape[c]	89	6.2	109 (104)	9.2 (6.6)
Potatoes	87	3.0	141 (127)	4.6(3.4)
Sugar-beet	163	7.0	217 (207)	10 (7.2)
Clover-grass ley	127	11	187 (181)	15 (11)
Lucerne	140	14	258 (252)	22 (15)
Reed canary grass	109	11	209 (204)	20 (14)
Salix	172	21	321 (317)	36
Logging residues				
After first thinning	9.5	21	12.6 (12.4)	31 (21)
After final felling	5.2	26	7.7 (7.6)	38 (26)

a Values without parentheses are based on fossil-fuel-based energy inputs and values within parentheses on biomass-based energy inputs.
b Energy yield - primary energy input. Values without parentheses are based on fossil-fuel-based energy inputs and values within parentheses on biomass-based energy inputs.
c Energy yield divided by primary energy input.
d For wheat including grain+straw, for rape including seed and straw.

It is possible to maintain the energy use in biomass transportation at a relatively low level in a system for large-scale use of biomass (Börjesson and Gustavsson, 1996). The potential demand for and supply of biomass in Sweden are relatively well matched geographically, and the transportation distances should thus be relatively short. Even if biomass were to be transported significant distances, energy use for this transportation can be relatively low, provided that rail or sea transport is used. To use the same amount of energy for transporting Salix chips as was required for their production (2-4% of the energy content of the Salix chips), they would have to be transported approximately 50-100 km by tractor, 150-250 km by truck, 300-500 km by train and 600-1000 km by sea (Börjesson, 1996). The cost of transportation will be a more important restriction to transport biomass long distances than large energy inputs.

Technologies for the use of biomass for heat production are commercial in small-, medium- and large-scale plants. Biomass can be used in many different forms, suitable for different applications. Processed fuels, such as briquettes, pellets and wood powder, are more expensive than wood fuel chips, but the plants in which they are used have lower investment and operating costs. Approximately 15% of the present biomass use in Sweden is for heating one- or two-dwelling buildings. So far, firewood billets (logs) have been the main energy carrier used in these buildings. In large-scale district heat plants, wood fuel chips are the main energy carrier due to their low cost. The market for processed fuels is, however, increasing. Using biomass for base-load heat production in district heating systems results in lower heating costs than using fossil fuels with current taxes and prices (Figure 3).

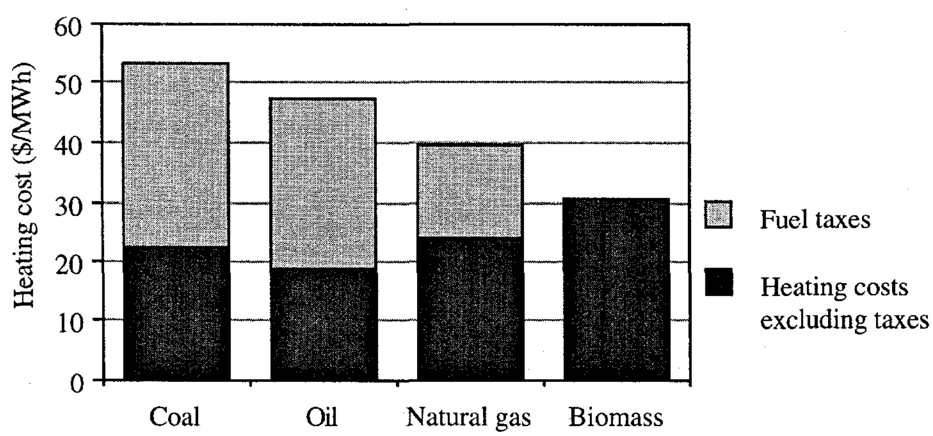

Figure 3. Heating cost for coal-, oil-, natural gas- and biomass-based boilers excluding and including current Swedish taxes. Investment, operation, and fuel costs are from Article IV, recalculated to the 1996 price level. Swedish taxes (from 1st of September 1996) on fossil fuels for heat production are US$ 26.8/MWh for coal, US$ 25.3/MWh for heavy fuel oil and US$ 14/MWh for natural gas (US$1 = SEK 6.64).

Biomass-based electricity is currently produced using steam turbines. The development of technologies for gasifying biomass for electricity production is in progress. Gasified biomass can be used in gas turbines or in a combination of gas and steam turbines, the combined cycle (CC) technique (Larson, 1993). CC technology will provide a higher electricity efficiency than will gas turbines or steam turbines used separately. In Article III it was shown that the use of CC technology for cogeneration of heat and electricity will, from a systems point of view, provide more energy efficient use of biomass, than the use of gas turbines or steam turbines separately. The article also showed, however, that electricity, at current biomass costs, may be produced at lower costs using gasified biomass in steam-injected gas turbines (BIG/STIG) than when using CC technology, although the electricity generating efficiency is lower for the BIG/STIG system. This is mainly the result of the significantly lower investment costs assumed for BIG/STIG. All cost data on technologies using gasified biomass are, however, uncertain as the technologies are not yet commercialised.

Biomass-based transportation fuels are receiving considerable attention both in Sweden and internationally. The Swedish Transportation and Communications Research Board are spending SEK 120 million over a three-year period for a development and demonstration programme for biomass-based transportation fuels. More than 100 buses are currently fuelled by biomass-based ethanol in Sweden (Swedish Transportation and Communications Research Board, 1995). In Brazil, biomass-based ethanol accounted for approximately 20% of the total transportation fuel demand in 1991 (Pilo, 1996). In the USA, alternative transportation fuels and oxygenates accounted for approximately 3% of the transportation fuel demand in 1993. Only a minor fraction of these (<25%) was, however, biomass-based.

Various transportation fuels produced from Swedish biomass are compared in Article V. It was found that the preferred fuel would be produced from cellulosic biomass rather than from conventional annual crops, such as oil plants, cereals and sugar-beet. This is a result of the more efficient utilisation of the land area (larger net energy yields), much lower production costs of the feedstocks, and of lower environmental impact from the biomass production. Technologies for producing transportation fuels from cellulosic biomass[27] are, however, not yet commercially available, although efforts are being directed towards the development of such technologies. Production of rape methyl ester and ethanol from sugar and starch crops is currently possible.

The use of energy carriers such as methanol, ethanol and methane gas (which can all be produced from biomass as well as from fossil fuels) could provide significant local and regional environmental advantages compared with the use of fossil fuels. The emissions of nitrogen oxides and particulate matter can be reduced by more than 50% if these fuels are used in heavy-duty vehicles instead of diesel (Article V). Many of the most

[27] The fuels studied from cellulosic biomass were ethanol, methanol and hydrogen.

hazardous VOCs will also be eliminated from the exhaust gases upon a change from petrol and diesel to alcohol fuels or methane gas. On-going technological development will, however, probably reduce emissions from both conventional and alternative fuels in the future, thus reducing the absolute advantage of using alternative fuels compared with conventional ones (Egebäck, 1996). The cost of achieving these emission reductions have, however, not been thoroughly assessed and might differ between fuels.

Alcohol fuels, hydrogen and methane gas are excellent fuels for Otto engines. Both performance and engine efficiency can be increased compared with petrol, if these fuels are used in Otto engines. Diesel engines have a higher average efficiency than Otto engines, and no major efficiency improvements can be expected for the alternative fuels compared with diesel. Hydrogen is the transportation fuel that could be produced from biomass at the highest efficiency and the lowest cost, but as the result of costly gas storage the use of hydrogen for fossil fuel substitution resulted in much higher costs for CO_2 reduction than did the use of methanol and ethanol (Article V). Technologies for producing hydrogen from methanol or other liquid fuels (e.g. ethanol or petrol) on-board the vehicle are, however, under development.[28] On-board production of hydrogen may be important for the future commercialisation of fuel-cell-powered vehicles as hydrogen is the preferred fuel for fuel cells. All studied biomass-based fuels resulted in higher costs than the use of fossil fuels and a valuation of environmental and other benefits must be included in a comparison to make biomass-based fuels competitive.

An area of debate is whether biomass resources should be used for heat-, electricity- or for transportation fuel production. This issue was addressed in Article IV by focusing on CO_2 reduction as the main reason for biomass use. Different applications in which fossil fuels could be replaced by biomass-derived fuels were compared with regard to the resource- and cost efficiencies of the CO_2 reduction (measured as ton C/ha, yr and as \$/tonne C). It was found that the most efficient way to achieve CO_2 reductions using biomass was to substitute fossil fuels used for heat production, followed by fossil fuels used for electricity production. The lowest efficiency was achieved by using biomass for transportation fuel production. The cost of CO_2 reduction is uncertain and differs between applications, but estimates in the present work indicate that they would be about US\$ 50-150/tonne C (1993 price level) when substituting fossil fuels for heat production, US\$ 50-175/tonne C when substituting fossil fuels for electricity production, and US\$ 180-340/tonne C when substituting fossil transportation fuels with biomass-based fuels.

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[28] It is also possible to produce hydrogen from methane on-board the vehicle. Liquid fuels are, however, preferred in vehicle applications as they are more easily stored in the vehicle.

The analysis in Article IV is based on the assumption that technology and fuel substitution will be made when new investments are required in heat and electricity production and in vehicles. Although Article IV gives an important indication of where biomass could be used most efficiently, further analyses of the dynamics of the energy system would be needed to determine when and in which applications fossil fuels should be substituted. Not only the age structure of existing technologies and the potential for energy improvements in different sectors are important, but also the desired pace of CO_2 abatement, and the final level of CO_2 emissions. Other environmental effects of different biomass uses and issues of supply security should also be considered. For example, local air pollution might have a significant impact on the value of using alternative transportation fuels in city areas (see Article V).

The question of in which sectors biomass should preferably be used is perhaps of most interest as long as the targeted CO_2 emission reductions are relatively limited. In Article VI, it is investigated whether there will be any Swedish biomass available for the transportation sector, if the substitution of fossil fuels used for heat and electricity production is prioritised over the substitution of fossil fuels used for transportation. If the most energy-efficient end-use technologies commercially available are used, and wind power production is increased to 20 TWh/yr, Swedish biomass can suffice, not only for Swedish heat and electricity production, but also for approximately 30% of the Swedish transportation fuel demand estimated for 2015. If more energy-efficient near-commercial end-use technologies are used, biomass would suffice for 80% of the transportation fuel demand. Furthermore, the Swedish CO_2 emissions would be reduced by more than 50% only in those scenarios in Article VI, where biomass also suffices for part of the transportation fuel production. If the increase in atmospheric CO_2 concentration is to be halted, global CO_2 emission reductions of more than 60% will be necessary (IPCC, 1990). CO_2 emission would then have to be reduced in all sectors, by not only using biomass, but by improving energy efficiency and utilising other renewable energy sources in addition to biomass.

With policies aimed at far-reaching CO_2 emission reductions, the incentives for both energy efficiency improvements and the use of non-fossil energy sources, such as biomass, wind or sun, will probably be increased. Increased CO_2 taxes will also increase the willingness to pay for biofuels, thereby strengthening bioenergy in competition with other agricultural alternatives, as well as the production of other forest products. An energy policy might therefore induce changes in other sectors, such as more efficient use of wood fibres, as a result of increasing prices for pulpwood driven by the pressure from the energy sector. Such intersectorial relationships would be interesting to analyse but this is outside the scope of this work.

4.3.2 *Hydro-, wind- and solar-energy*

Hydro power has been an important energy source since the middle ages with major expansion starting at the end of the 19th century. Approximately 15% of the global electricity supply and half of the Swedish electricity supply is from hydro-electric plants (IEA, 1995; NUTEK, 1996). Hydro-electricity production is capital intensive but has low operating costs. The large fraction of hydro power in the Swedish electricity system has a major impact on the ability of the electricity supply to follow demand, a fact which would reduce the cost of integrating intermittent energy sources, such as wind and solar power into the electricity system. An important environmental effect of hydro power is the impact of large water reservoirs used to regulate the water flow through the hydro power plants. The environmental effects are site-specific, depending on topography, river flow, climate, ecology, and land use. The effects may be both a result of the land inundation per se, and of emissions of greenhouse gases from the flooded area. The social impact of the construction of large dams may be significant and may require considerable human migration. The building of new hydro power plants in Sweden is heavily restricted, and the exploitation of the four remaining unexploited major rivers in Sweden is prohibited by law.[29]

Wind power has been expanding during recent years with an increase in global capacity from 2 GW to almost 5 GW between 1990 and 1995 (Sørensen, 1995; Windpower monthly, 1996). The countries with the largest installed wind power capacity are the USA, Germany, Denmark and India.

In Sweden the wind power capacity has risen rapidly during the 1990s, but still contributes to less than 1‰ to the total electricity supply. An Official Report of the Swedish Government (1988) estimated the theoretical potential for on-shore wind power in Sweden to be 35-70 TWh/yr, assuming 300-500 m safety distances. More stringent restrictions, motivated mainly by aesthetic and military reasons, reduced this potential to 3-7 TWh/yr. Some 20 TWh/yr was found suitable for wind power production off-shore. A potential production of 25 TWh/yr would be equal to approximately 15-20% of the current Swedish electricity production.

The cost of producing electricity from wind power has decreased continuously during the 1980s and 1990s, while the rated machine power has increased from around 50 kW in the early 1980s to about 500 kW today (Cavallo and Hock, 1993; Sørensen, 1995; van Wijk, 1996). New on-shore wind power plants can, in suitable locations, produce electricity at costs competitive with those of new fossil-fuel-fired power plants. Off-shore

[29] According to the Natural Resources Act, 1987:12

wind power plants account for the largest fraction of the Swedish wind power potential (Official Report of the Swedish Government, 1988). The investment and annual operation costs will be higher for off-shore wind power plants. Some of these cost disadvantages will, however, be counteracted by the fact that off-shore locations are generally more windy than on-shore locations, thus resulting in higher annual electricity production per unit installed capacity.

The environmental impact of wind power is largely a land-use question. Although the direct land requirement is very low compared with other renewable energy sources the locations may be quite widespread. Wind power plants cannot be located too closely to each other because of the impact this would have on wind capture. The aesthetic impact is a factor often discussed in connection with wind power. Public acceptance depends, amongst other factors, on education and participation in siting decisions. Furthermore, a positive attitude towards renewable energy in general makes people less concerned about the visual impact of wind power plants (Grubb and Meyer, 1993). Nevertheless, especially sensitive areas may be excluded from wind energy development. Noise has often been cited as a major problem for wind energy. Although it is impossible to eliminate all noise, modern turbines produce noise which is only slightly above general wind noise levels (Grubb and Meyer, 1993). The risk of noise disturbance can be reduced by locating the wind power plants at some distance from residential buildings. Concern about noise disturbance was a significant restriction on the location of areas for wind power plants suggested by the Official Report of the Swedish Government (1988).

In Sweden, most wind electricity is produced during the autumn and winter when the electricity demand is high (Official Report of the Swedish Government, 1988). This is advantageous for the integration of wind power into the electricity system. Furthermore, the large fraction of hydro power in the Swedish electricity system can be used to compensate for the uneven temporal distribution of wind power supply. There seem to be no technical obstacles to integrating 30 TWh/yr wind power into the Swedish energy system. The integration costs per unit wind energy supply increase, however, with installed wind power capacity (Mårtensson, 1994, L. J. Nilsson, 1993).[30]

Solar energy can be utilized through passive heating, for active solar heating through a thermal heating system, and for electricity production using either solar-thermal or photo-

[30] The most important reason why marginal integration costs increase with installed wind capacity, is that the short-term regulation costs increase. These costs occur as a result of the increasing hourly variation in hydroelectric output, which results in lower conversion efficiency of the hydro power plant (Nilsson, 1993). Increasing wind spills and higher demand for spinning reserves in thermal power plants also contribute to increased integration costs. Estimates of integration costs for wind power are uncertain. Whereas Vattenfall AB estimates the average integration cost for 30 TWh/yr to be approximately 2 US cents/kWh, Nilsson (1993) estimates it to be 0.6 US cents/kWh (1988 price level) (see Nilsson (1993) for a discussion).

voltaic (PV) technologies. Passive solar heating provides approximately 5-10% of the heat demand in Swedish buildings (Carlsson, 1992). Active solar applications for space and hot-water heating can be installed both in individual buildings and in district heating systems. Solar systems with seasonal storage covering 75% of the space and hot water heat demand have been designed in Sweden (Tönsing, 1996). The cost of electricity from solar-thermal power plants and PV cells is still much higher than, for example, cost of electricity from wind and biomass. The costs of solar electricity is, however, continuously decreasing as investment costs per m^2 are decreasing and efficiencies are increasing. The solar inflow is significantly lower in Sweden than in, for example, southern USA, southern Europe and most developing countries. Furthermore, high inflow in the summer coincides with a low electricity demand. Both these aspects will probably make direct solar electricity utilisation less important in Sweden than, for example, in parts of the USA and the developing countries.[31]

[31] The global potential for solar energy is enormous. For example, by using only 2 % of the global desert area for solar electricity production, hydrogen could be produced in an amount equal to present global fossil fuel consumption (Ogden and Nitsch, 1993).

5. Efficient and low-pollution energy systems

The potential effects on emissions and costs of combining efficient energy systems with low-pollution fuels and supply technologies are analysed in Articles I and II and, to some extent, in Articles IV and VI. In the scenarios in Article I, it was shown that NO_x and SO_2 emissions from the energy system (excluding transportation) in western Scania could be reduced by 50% in 2010 compared with 1988 if the best available end-use technologies were used, if cogeneration were expanded, and low-pollution energy conversion technologies were used. Such a system, based on natural gas, would have significantly lower costs than a system based on condensing plants and end-use technologies with efficiencies equal to those on average used in 1988, and it would have significantly lower emissions of NO_x, SO_2 and CO_2. The emissions of CO_2 would, however, also in the system based on cogeneration and best-available end-use technologies, be 30% higher in 2010 than in 1988, mainly as a result of the decision to phase out Swedish nuclear power. The CO_2 emissions would, however, be 25% lower than in 1988, if the regional biomass and on-shore wind energy potentials were used instead of fossil fuels in this cogeneration-based energy system, with the best available end-use technologies. The 40-50% lower CO_2 emissions in the renewable-based energy system, compared with the natural-gas-based system was achieved, with an average CO_2 reduction cost of $US\$_{1989}$ 45 - 75/tonne C.[32]

Utilising near-commercial end-use technologies and increasing the use of renewable energy sources to include off-shore wind power would enable CO_2 reductions of more than 80% compared with 1988.

In Article II it was shown that the emission of NO_x from the Swedish transportation sector could be reduced by more than 50% by 2015 only by implementing the best available vehicle technologies. Using the best available technologies for fossil fuels would, however, only suffice to stabilize CO_2 emissions at the 1991 level. With near-term commercial technologies, a CO_2 reduction of about 20% would be possible. Utilising biomass instead of fossil fuels for road transport would reduce the total transport CO_2 emissions by 80% at an estimated cost of $US\$_{1993}$ 260/tonne C.[33] Using best available technologies would not increase direct costs compared with if average sold technologies were used.

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32 Other cost estimates in this essay are in 1993 price level. The consumer price index in the US was approximately 15% higher in 1993 than in 1989.

33 A more well-developed estimate of the costs for CO_2 reduction when substituting biomass-based transportation fuels for fossil fuels are shown in article V. The values in article II and V correspond, however, relatively well.

In Articles IV and VI only CO_2 emissions were studied but, on the other hand, the whole Swedish energy system (heat, electricity and transportation sectors) was included. It was shown that, by utilising the Swedish biomass potential, it would be possible to avoid any increase in CO_2 emissions as a result of the closure of Swedish nuclear power stations, even if energy use were to remain at the current level (Article IV). With a 30% reduction in energy use, CO_2 emissions could be reduced by 50%. No cost estimates were made for these scenarios. The cost of reducing CO_2 emissions from 1992 fossil fuel use by 7.5 Mtonne C (equal to 50% of current Swedish emissions) by substituting biomass for fossil fuels was, however, estimated to be approximately US$ 1,100 million annually (average reduction cost US$150/tonne C) representing 0.6% of the 1993 Swedish GNP.

In Article VI, more elaborated end-use scenarios were created compared with those in Article IV. It was shown that a combination of energy efficiency improvements and utilisation of Swedish biomass and wind energy resources could result in a more than 50% reduction in CO_2 emissions by 2015 compared with the 1989 level. No cost estimates were made as the aim of this paper was to assess whether the physical potential of biomass would be large enough for providing the transportation sector with any significant amount of transportation fuels.

6. Policy discussion

Although several options for reducing environmental impact from energy use and transportation have been identified in this work, many of these will not be utilized without the introduction of relevant policies. Such policies would probably include economic incentives, regulations, R&D support for new technologies and information.

The use of energy results in external costs that are not internalised in the cost to the users.[34] This may result in a higher energy use, more kilometres driven, and the use of more environmentally harmful energy sources than are optimal for society as a whole. The main external cost from energy use results from the emission of pollutants to the air. In the transportation sector, noise, accidents, congestion and infrastructure wear also result in high external costs.

Several methodological problems are associated with estimating the external costs of heat and electricity production and of transportation. First, it may be extremely difficult to estimate the environmental impact of a certain emission. For many pollutants, the effect depends on the location of the polluter, the climate, etc.[35] The potential environmental effect of greenhouse gas emissions is probably large, but the details are very uncertain and may include the risk of large unpredictable changes in climate systems (IPCC Working Group I, 1996). The cost of a certain environmental impact is difficult, or sometimes even impossible, to assess accurately. Some aspects, such as physical damage to buildings or reduced productivity in agriculture are easier to estimate than, for example, the cost of large-scale climate changes resulting from increased CO_2 concentrations in the atmosphere. The marginal damage costs due to CO_2 are very sensitive to, for example, discount rates and equity aspects and estimates vary by orders of magnitude.[36]

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34 External costs can be defined as costs which arise when the social or economic activities of one group of people have an impact on another, and when the first group fails to fully account for its impacts.

35 For example, the cost of NO_x emissions has, due to different human exposure to air pollution, been estimated to be SEK 40/kg if the NO_x is emitted in the countryside, SEK 90/kg on average for the city of Gothenburg, SEK 340/kg on average for central Gothenburg and SEK 760/kg during inversion (Leksell and Löfgren, 1995). The cost for the countryside is based only on regional damage costs, whereas the costs in cities are based on estimates of the dose to which the population will be exposed and the health effects this dose will cause. In 1995, 1 US$ was approximately 7 Swedish crowns (SEK).

36 For example, Nordhaus (1993) estimated the cost of CO_2 emissions to be US$ 10/tonne C, while Azar and Sterner (1995) estimated them to be US$ 250-590/tonne C. The higher value in Azar and Sterner is almost completely due to the choice of discount rate and the weight assigned to the costs in the developing world so that they reflect real welfare losses. With the estimates of Azar and Sterner, many of the options studied in this thesis may be economical (for example biomass use for heat, electricity and transportation fuel production), whereas estimate of Nordhaus will allow significantly fewer options for CO_2 reduction. It should be mentioned that both studies are based on similar assumptions of the damage cost as a percentage of the future world income, a factor which is also very uncertain.

According to current Swedish transport policy, external costs should be included in the cost to the driver. Several studies have shown, however, that taxes are significantly lower than the external costs. For example, O. Johansson (1995) estimated that the external costs for road transport was approximately SEK 50,000 million/yr in 1993 (≈3-3.5% of the Swedish GDP), of which about 50% was related to air pollution and noise. Taxes collected from road transport were approximately SEK 30,000 million/yr the same year. Studies also show that external costs resulting from heat and electricity production may be significant compared with the direct production costs (Ottinger et al., 1990, ExternE, 1995).

In policies for sustainable energy and transportation systems it is important that the external costs involved in energy use and transportation are included in decision-making. Many of the options for dealing with the environmental problems connected with energy use will not be competitive if decision-making criteria were only based on direct costs. The concept of external costs could be used, for example, for designing taxation systems, and systems for road pricing.

Some parts of the energy system are directly subsidised by governments. The reason for this may be to encourage the exploitation of domestic resources or to encourage specific technologies. The World Energy Council Commission (1993) concluded that commercial energy prices in transitionary and most developing countries are subsidised at an average rate of between 30 and 50%. Such subsidies support higher energy use than that which is economically justifiable.

To encourage new technologies, however, subsidies may be appropriate to support development efforts and to allow markets to grow so that new technologies can gain scale advantages. One special area of interest may be vehicles, where mass production is one of the main reasons for low production costs and where new technologies will have difficulties in competing before they have gained a significant market share. Williams and Terzian (1993) similarly showed that governmental subsidies of photovoltaic electricity may result in economic gains as a fast introduction of this technology may result in fast cost reductions due to the learning often found in industrial production systems.

There are several organisational and economic barriers to utilising energy-efficient technologies, even if they appear to be profitable in socio-economic analyses. The end-users are often not aware of the energy use of different appliances and of the potential to reduce the overall costs for the user. Energy costs are often very small compared with other costs and thus receive little attention. End-users often require one to three year pay-back times on investments in energy efficiency, implicitly assuming approximate discount rates of 100 to 30 percent, which is much higher than the discount rate used for investments in energy supply (Christiansson et al., 1995). This may reduce the economic efficiency of the energy system as investments in new energy supply technologies become more economic than investments in EEIs. Instruments to overcome these barriers to energy efficiency may include, for example, information programmes, loan and performance contracting, rebate programmes and energy performance standards (Christiansson, 1996).

Regulation has historically been very effective in reducing emissions from vehicles and electricity and heat production plants. Regulation through, for example, emission and energy efficiency standards will probably be important complements to economic incentives in future energy and environmental policies.

Many of the technologies discussed in this thesis will require continued R&D to be commercially available. Energy R&D spending has been declining since the beginning of the 1980s. Furthermore, government energy R&D budgets have been dominated by research on nuclear fission and fusion rather than on the areas of energy conservation and renewable energy discussed in this thesis (IPCC Working Group II, 1996).

7. Conclusions

Energy use is responsible for a large fraction of the emissions of air pollutants, resulting in local, regional and global environmental problems. In this work it has been shown that the implementation of commercially available technologies and near-commercial technologies, would reduce NO_x, SO_2, and CO_2 emissions significantly in 20-25 years' time, compared with current levels.

NO_x and SO_2 emissions from electricity and heat production in western Scania can be reduced by more than 50% and the emissions of CO_2 by 25% by 2010, compared with 1988 levels using an energy system based on the most energy efficient technology commercially available, cogeneration, renewable energy sources and low-pollution energy conversion technologies. Implementing the best available vehicle technology in a fossil-fuel-based Swedish transportation system would reduce NO_x emissions by 50% by 2015, compared with 1991, and stabilize CO_2 emissions at the 1991 level. The introduction of biomass to the transportation sector would allow even greater CO_2 reductions.

Swedish biomass resources are large, and, assuming production conditions around 2015, about 200 TWh/yr could be utilized for energy. Utilising this potential and a wind-power production of 20 TWh/yr would result in a reduction of Swedish CO_2 emission by more than 50% compared with 1991, even with a growing demand for energy services and a closure of Swedish nuclear power stations, provided that the potentials for end-use efficiency improvements and cogeneration of heat and power are utilized.

Biomass could be used efficiently for heat, electricity and transportation fuel production, and major reductions in CO_2 can be achieved when substituting biomass for fossil fuels. The cost of CO_2 reduction is uncertain and differs between applications. It has been estimated in this thesis that they would be about US$50-150/tonne C when substituting fossil fuels for heat production, US$50-175/tonne C when substituting fossil fuels for electricity production, and US$180-340/tonne C when substituting fossil transportation fuels with biomass. Transportation fuels from cellulosic biomass is likely to be less expensive than transportation fuels from conventional biomass feedstocks such as oil plants, sugar-beet and cereals.

The large potential emission reductions will probably not be achieved without the implementation of policy measures. Economic incentives, regulations and R&D support are some of the options that could form part of a strategy for a sustainable energy system.

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